INTENSITY DEPENDENT EMITTANCE-EXCHANGE IN A HIGH INTENSITY PROTON SYNCHROTRON

I. Sakai, S. Machida, T. Adachi, Y. Arakida, Y. Irie, K. Kitakawa, Y. Mori, Y. Shimosaki,
H. Someya, M. Yoshimoto
KEK, 1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305-0801, Japan

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1. Introduction

The acceptance of the KEK booster has large side value (80 π mm mrad in the horizontal plane and 18π mm mrad in the vertical plane).

To increase the beam intensity we have been trying to achieve painting injection in the horizontal plane.

The intensity-dependent emittance-exchanges in the horizontal and vertical plane were observed.

In order to clarify the experimental results, multi-particle tracking was performed with self-consistent space-charge forces.

The experimental and simulation results imply that a space-charge potential of a beam-induced coupling exist between the horizontal and vertical planes.

2. Painting injection in the horizontal plane to increase the beam intensity of the booster

2.1 Structure of the KEK Booster

The features of the 500-MeV KEK booster are rapid cycling (20Hz), very compact and comprising combined function magnets.

It supplies proton beams to the 12-GeV main ring (MR) and the neutron and meson science laboratory (NML).

The MR demands to control the extracted beam emittance from the booster for optimum injection and the NML demands the beam intensity as high as possible.

The normalized value of the designed acceptance of the KEK booster is 80π mm mrad in the horizontal plane and 18π mm mrad in the vertical plane.

The incoherent space charge limit of the booster was calculated to be $3.2*10^{12}$ ppp assuming the designed acceptance of the machine.

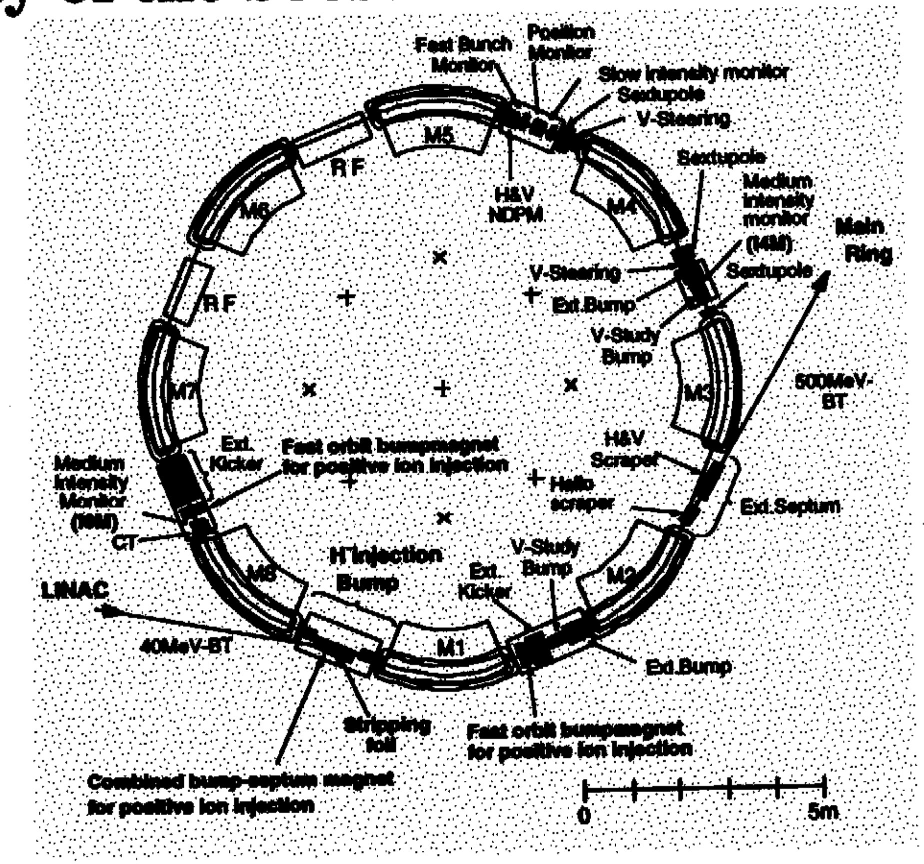


Fig.1 Structure of the KEK Booster

2.2 Injection System

The injection system of the KEK booster consists of four bump magnets for normal H^- injection, two fast orbit-bump magnets for orbit shift painting to form a uniform distribution and two steering magnets on the injection beam line, which adjust the width of the horizontal painting.

The position and angle of the injection point for charge-exchange injection are fixed by the closed-orbit bump magnets, and the center of the closed orbit at the injection point can be shifted by two orbit bump magnets which are placed at the upstream and the downstream positions.

At the each position of orbit shift bump magnets, the phase of betatron oscillation leads and lags by p/2 from the injection point.

Beams are injected gradually from the center of phase space to the outside by a shift of the closed orbit, which is controlled by the decay pattern of the magnetic field of these two bump magnets.

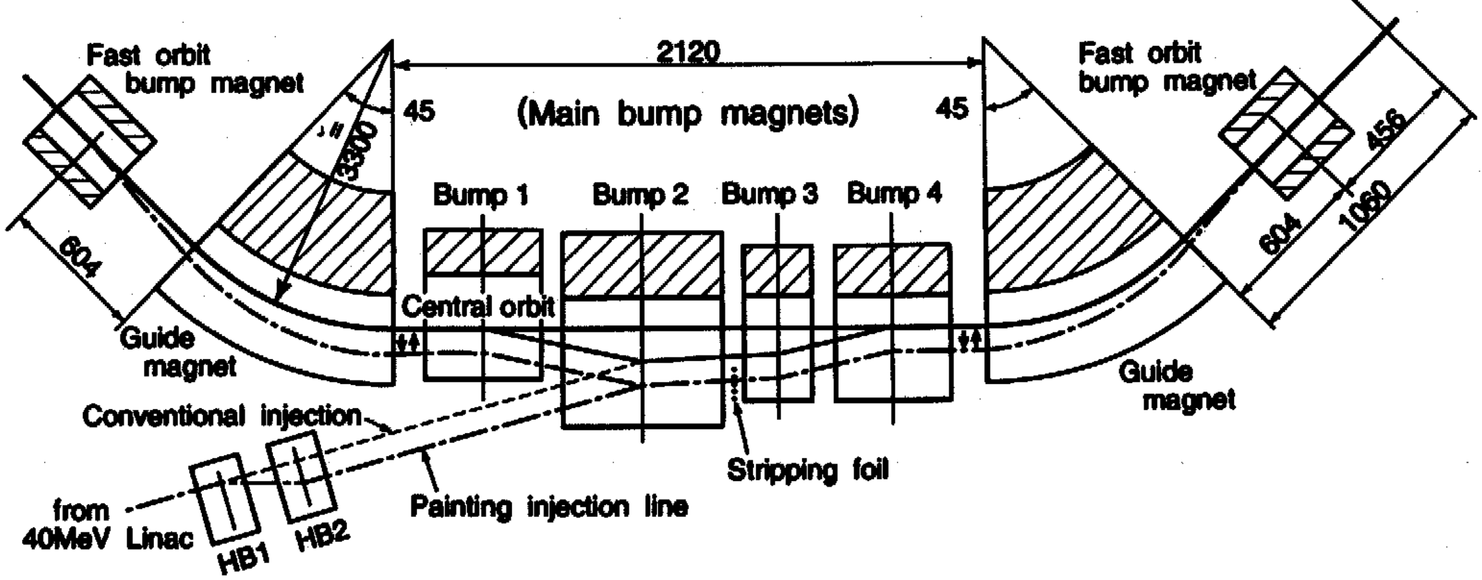


Fig.3 Injection System

2.3 Acceptance & Beam Emittance

The normalized value of the designed acceptance of the KEK booster is 80 π mm mrad in the horizontal plane and 18 π mm mrad in the vertical plane.

The incoherent space charge limit of the booster was calculated to be $3.2*10^{12}$ ppp assuming the designed acceptance of the machine.

Until now, a beam intensity of 2.2^{12} ppp was constantly obtained by normal H^- injection.

At this beam intensity, the emittance of the extracted beams is 38 π mm mrad in the horizontal plane and 27π mm mrad in the vertical.

The value of the vertical emitttance already exceeds the designed acceptance of the machine.

The increase of the vertical beam size seems to restrict the beam intensity.

But the horizontal emittance of the extracted beams is half the value of the full acceptance of the machine.

It had been expected that the beam intensity might increase by 25%, if the horizontal emittance is extended to the full acceptance of the machine by painting injection.

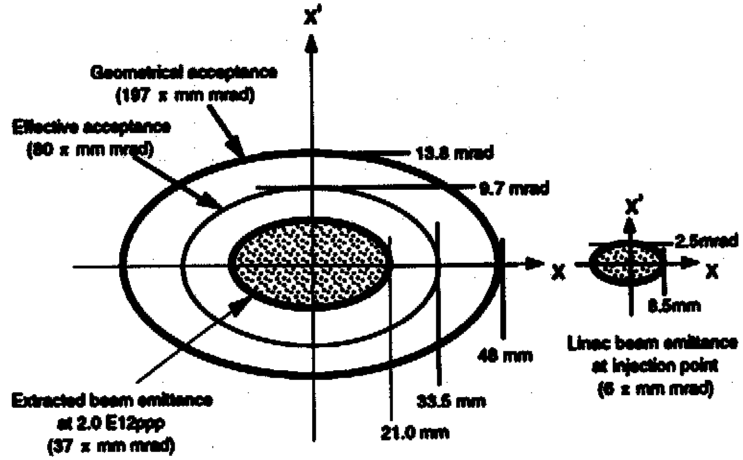


Fig.3 Horizontal Acceptance & Beam Emittance

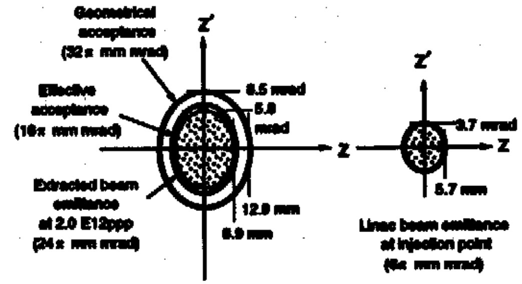


Fig.4 Vertical Acceptance & Beam Emittance

2.4 Experimental Results of the Particle Distribution in the Real Space

During charge exchange injection the beam is painted on the horizontal phase space.

By changing the decay current of orbit shift bump magnets, the circulating beam orbit during an injection period was moderately shifted for stacking in desired distribution.

To examine the effects of the orbit shift bump magnet, the particle distributions in the real space were measured using the multi-wire profile-monitors in the extracted beam line.

The output signals of the profile monitor in the horizontal plane are shown in Fig.5.

Solid triangles indicate the normal injection overlapped on the central orbit.

Open circles indicate the off-center injection by 15mm parallel shift of injection line, which shows hollow beam distribution.

Solid squares indicate the painting injection using the orbit shift bump magnet, which show the flat distribution in the middle area.

The vertical distributions are shown in Fig.6.

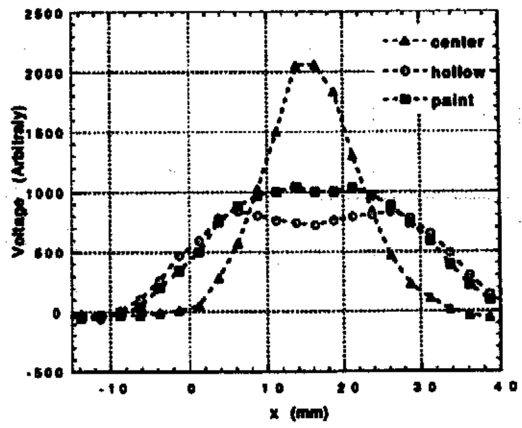


Fig.5 Horizontal Distribution

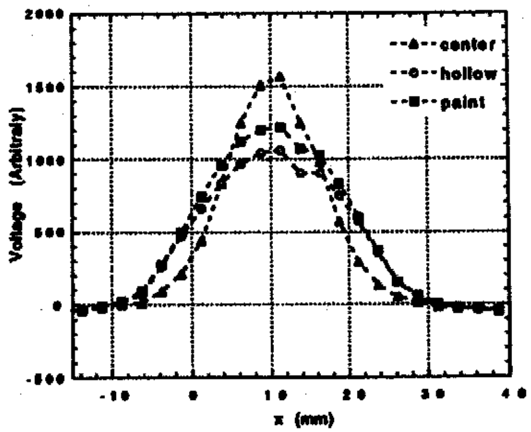


Fig.6 Vertical Distribution

3. Intensity Dependence of the Extracted Beam Emittance

3.1 Expansion of Extracted Beam Emittance by Off-Center Injection

The extracted beam emittance with the width of off-center injection in the horizontal plane as the parameter of the beam intensity is shown in Fig.7.

In the low-intensity mode, the increments of the horizontal emittance give good agreement with the calculated values by the width of the off-center injection, and the vertical emittance is only little affected by the horizontal expantion of the emittance.

It can be considered that the emittnce is conservative through the accelerating process.

On the other hand, in the high-intensity mode, although, the injected beams of the booster were expanded by off-center injection, the horizontal emittance dose not increase

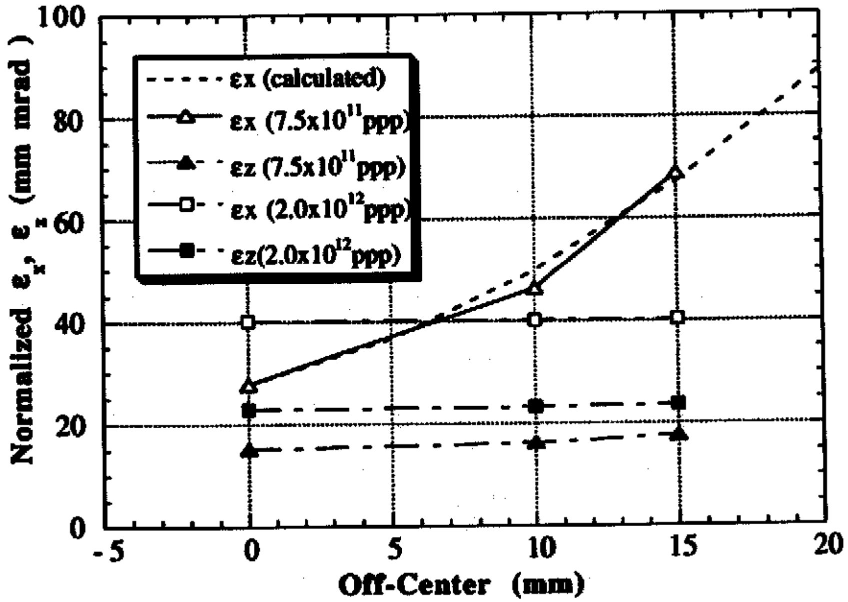


Figure 7: The extracted beam emittance with the width of off-center injection as the parameter of the beam intensity.

3.2 Shrinkage and Blow-up of Extracted Beam Profiles

Horizontal and vertical beam profiles under the 15mm off-center injection in the horizontal plane as parameters of the beam intensity are shown in Fig. 7and Fig. 8.

In the low-intensity mode, the extracted beam profiles coincided with the calculated values at injection in a simulation in which the space charge effects were not included.

In the high-intensity mode operation, 2.0×10^{12} ppp, extracted beam profiles are not directly reflected by the situation of the painting injection. The distributions of injected beams are no longer conserved.

In horizontal plane, the width of the extracted beam profile shrinks compared with low-intensity mode operation.

On the other hand, in vertical plane, the extracted beam profiles blow-up in the vertical plane.

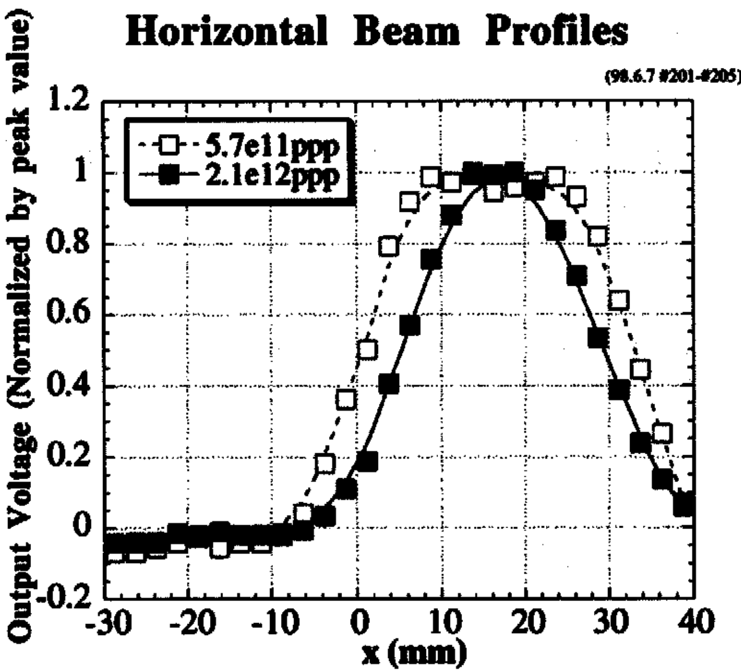


Fig. 8

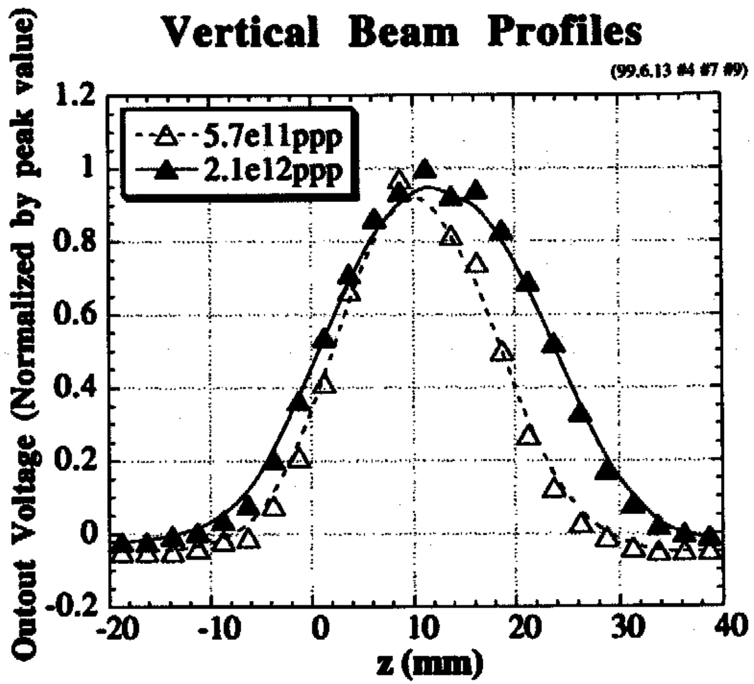


Fig.9

3.3 SIMULATION RESULTS

In order to clarify the experimental results, multi-particle tracking was performed with self-consistent space-charge forces.

The space-charge forces are modeled in the 2D plane (transverse only).

Multi-turn injection is simulated by adding a constant number of macro particles turn by turn.

As a result, the forces increase linearly as a function of time (or turn) and reach the maximum when injection is completed.

In reality, the line density increases further after the injection period, because of a bunching process, that was not included in this study. We assume that the emittance of an incoming beam is 1π mm-mrad in both planes.

When a linac beam is injected off center in the horizontal plane, a resultant distribution in the booster becomes hollow.

Thus, the projected profile on the position has a plateau as shown in Fig.10 (H).

On the other hand, the beam is injected on axis in the vertical direction and the distribution remains the same as the incoming beam (Fig.10 (V)). That is the case when space-charge effects are turned off. It is no longer true when space charge ($2.7*10^{12}$ ppp) is included.

Just as the experimental results show, the horizontal outline of beam size is decreased and the vertical one is increased in turn, indicating an emittance exchange between the two planes (Fig.11 (H) and (V)).

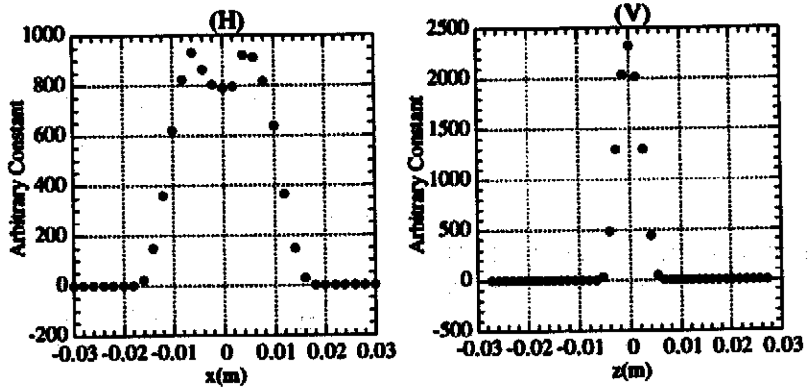


Figure 10: Simulation results of the projected profile (Space-charge effects are turned off)

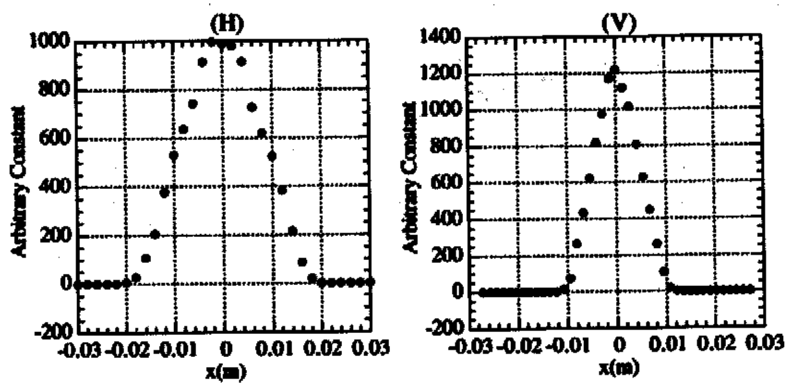


Figure 11: Simulation results of the projected profile_ (Space charge ($2.7*10^{12}$ ppp) is included)

3.4 Intensity Dependence of the Extracted Beam Emittance in the Case of Off-Center Injection in the Horizontal Plane

The intensity dependence of the extracted beam emittance in the case of 15mm off-center injection is shown in Fig. 12.

The extracted beam emittance is measured by multi-wire profile monitors at the dispersion-free points on the extracted beam line.

The off-center painting injection is tried only in the horizontal plane.

In the vertical plane, the injection point and angle are adjusted to the center of the phase space to obtain the minimum emittance in the vertical plane.

The horizontal emittance decreases with the beam intensity nevertheless the injected beam is expanded to the full acceptance by the 15mm off-center injection.

On the other hand, vertical emittance increases with the beam intensity.

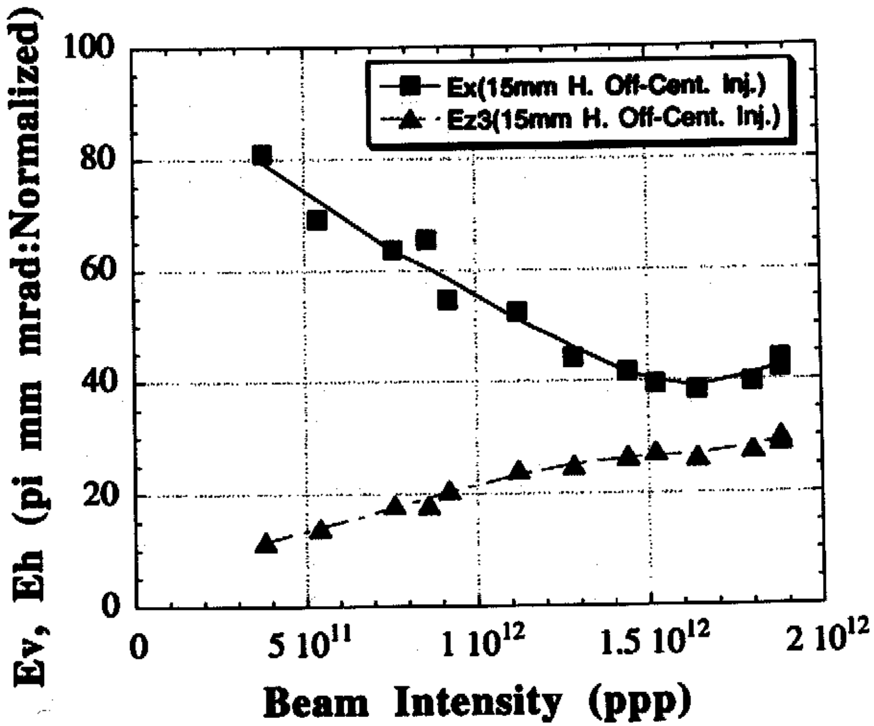


Figure 12: Intensity dependence of the extracted beam emittance as the parameter of the off-center injection.

4. Emittance exchange through accelerating process

4.1 Measurement of the circulating beam envelopes by bump magnets and scraper method

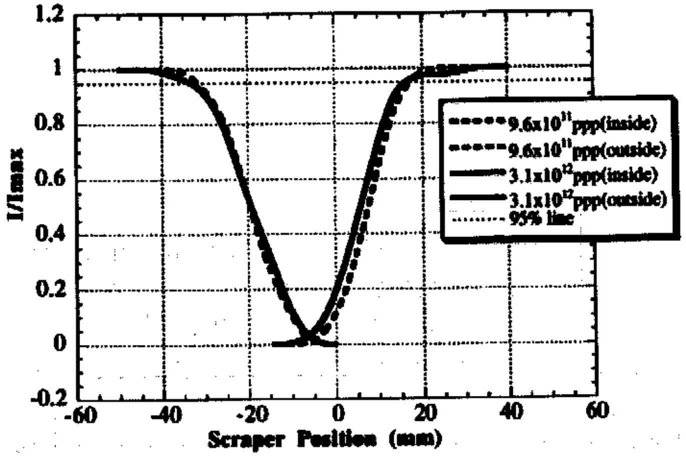
The horizontal beam sizes, which are expanded to full acceptance by off-center injection, were measured in a period of 0.06ms to 1.5 ms after injection, where the injected coasting beams were captured in a RF bucket.

In this bunching process, the momentum spread and the line charge density increases in a RF bucket.

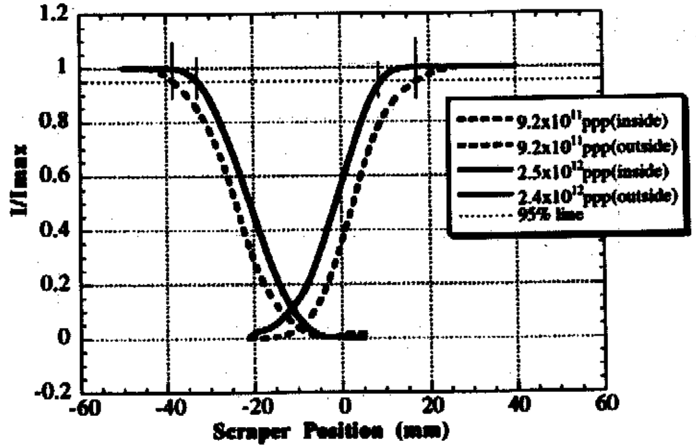
The bunching factor decreases from 1.0 to 0.4 in this period (from 0.06ms to 1.5 ms after injection).

The typical values of the beam size measured by the scraper method are shown, where the data are 0.06ms and 1.5ms after injection, respectively.

In Fig.13, at the 1.5ms after injection, the whole beam size of the high-intensity mode is clearly decreased compared with the low-intensity mode.



0.06ms after injection



1.5 ms after injection

Fig.13 Scraper Profiles

4.2 Measured Values of the Circulating Beam Sizes

The horizontal beam sizes, which are expanded to medium acceptance and full acceptance by off-center injection were shown in Fig. 14a and Fig.14b respectively.

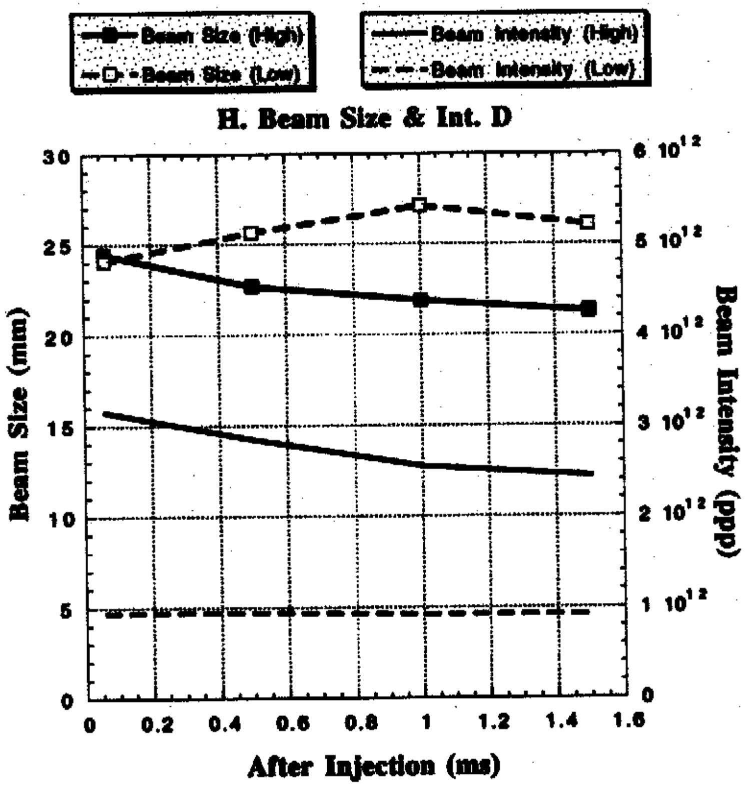


Fig. 14-a Measured Value of the Circulating Beam Envelopes in the Horizontal plane.
(Extended to the medium area of the acceptance)

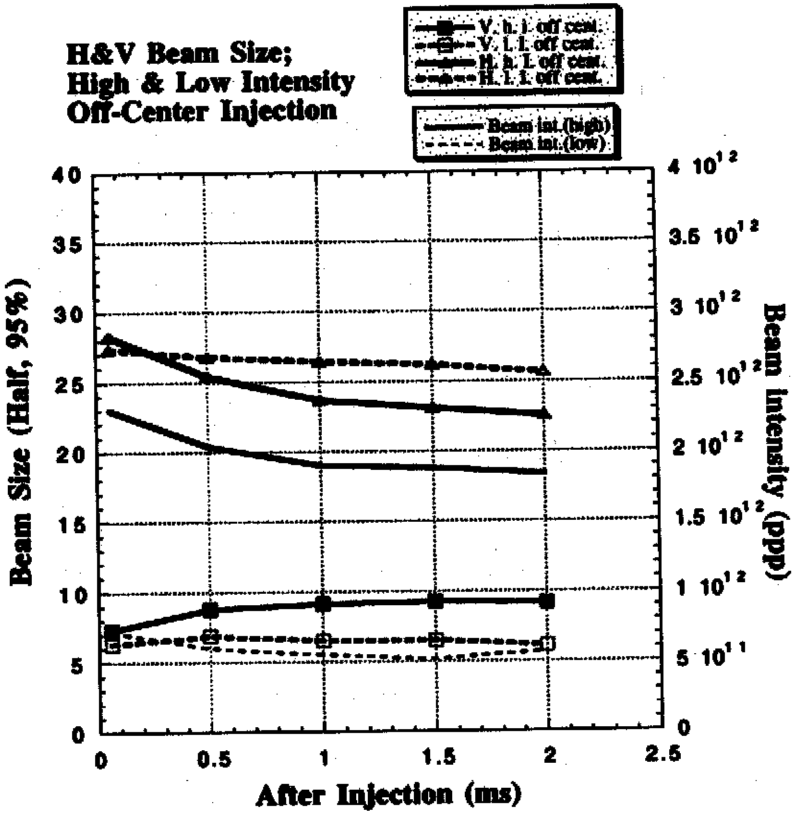


Fig. 14-b Measured Value of the Circulating Beam Envelopes in Horizontal and Vertical plane.
(Extended to the full acceptance)

4.2 Measured Value of the Circulating Beam Envelopes and the Conversion to the Beam Emittance

The horizontal beam sizes, which are expanded to medium acceptance and full acceptance by off-center injection were shown in Fig. 14a and Fig.14b respectively.

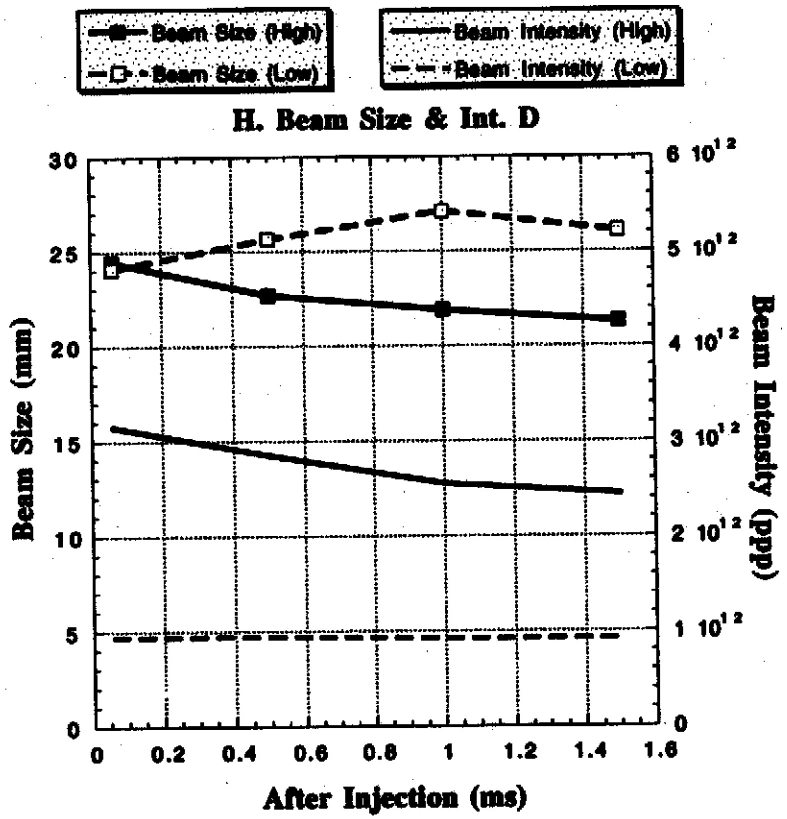


Fig. 14-a Measured Value of the Circulating Beam Envelopes in the Horizontal plane.

(Extended to the medium acceptance)

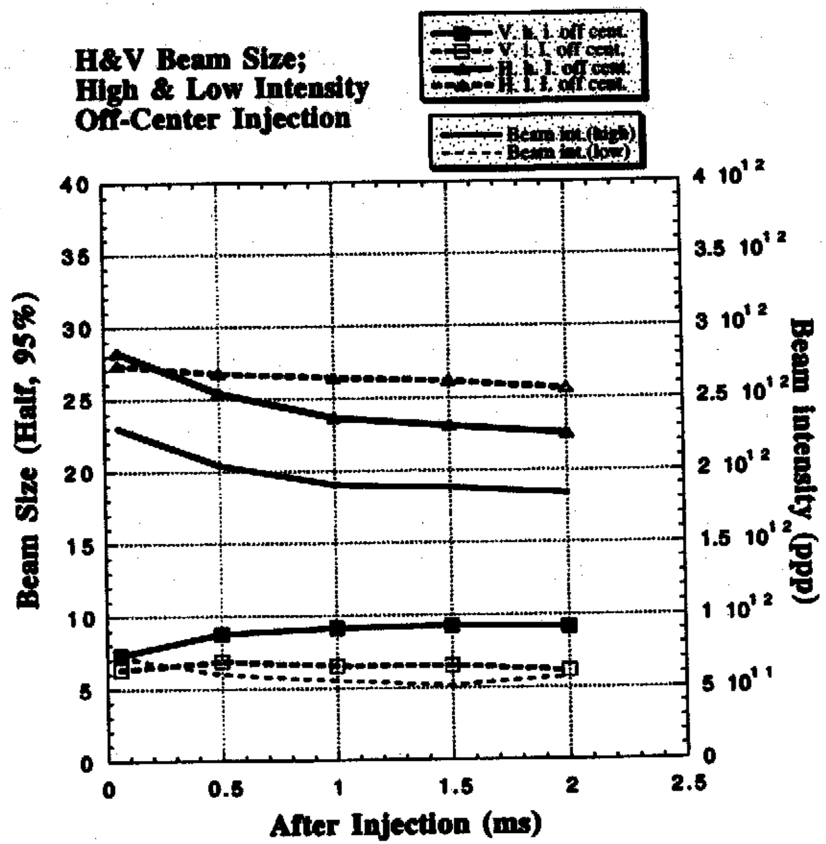


Fig. 14-b Measured Value of the Circulating Beam Envelopes in Horizontal and Vertical plane.

4.3 Estimation of the Beam Emittance from the Measured Value of Circulating Beam Envelopes

In the bunching process, the momentum spread and the line charge density increases in an RF bucket. The bunching factor decreases from 1.0 to 0.4 in this period (from 0.06ms to 1.5 ms after injection). The momentum spread increases ±0.3% to ±1% in this period.

Because the momentum dispersion at the scraper position is not zero (1.4m) in the horizontal plane and the momentum spread is not constant throughout the accelerating process, we cannot directly calculate the beam emittance from the whole beam size.

However, under the assumption that the momentum spread has the same value at the same time after injection, irrespective of the beam intensity (neglecting the beam loading in RF acceleration and space charge effect on the RF bucket), the difference in the beam size is considered to be the difference in the emittance due to the beam intensity.

The emittance is conserving throughout the accelerating process in the low-intensity mode; that just after injection can be deduced to be the same value as the extracted beam emittance, which is measured by a multi-wire profile monitor.

As shown in Fig.14, the beam size of the high-intensity mode and that of low-intensity mode are almost the same at the 0.06ms after injection.

The decrease in the horizontal emitttance in the high-intensity mode can be deduced by the differential value of the beam size with that of the low intensity mode.

The circulating beam emitttance 1.5ms after injection is close to the extracted beam emitttance

4.4 Circulating Beam Emittance Estimated by the Beam Envelopes

In the high-intensity mode operation, a decrease in the horizontal emittance and the increase in the vertical emittance take place simultaneously during the period from 0.06ms (or faster) to 1.5ms after the beam injection has been completed.

The vertical emittance growth reaches to the acceptance limit of the vertical plane.

The experimental results suggest the existence of an X-Y coupling resonance by space-charge effects.

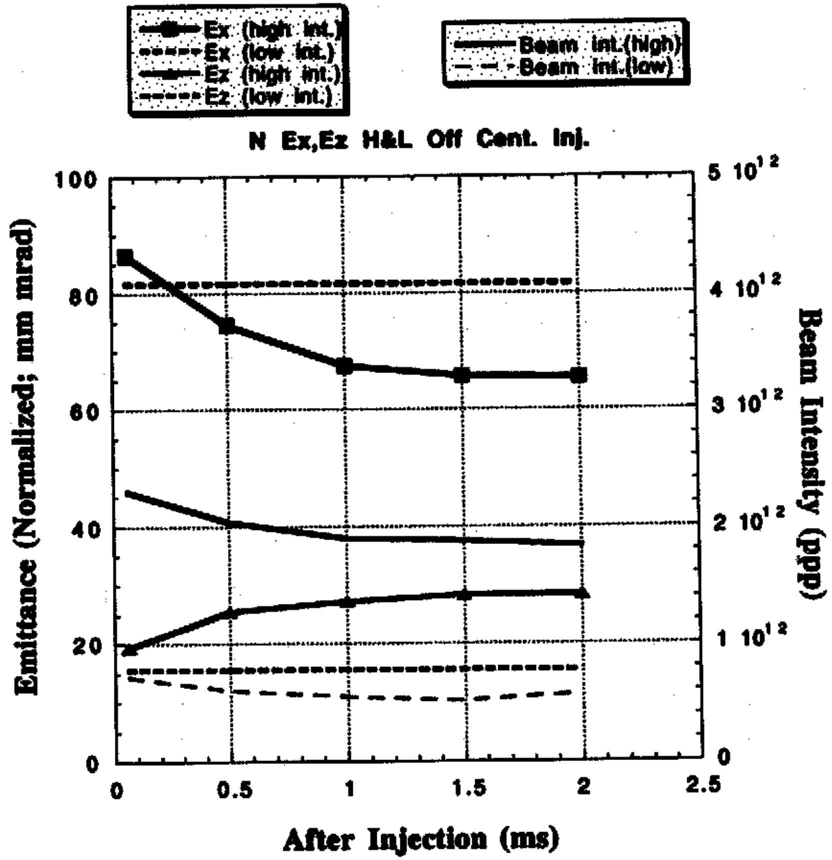


Fig.15 Normalized Ex, Ez Through Accelerating Process Just After Injection as a Parameter of High & Low Beam Intensity under the Horizontal Off Center Injection.

5. Three Dimensional Tracking Simulation with Space Charge

5.1 Horizontal and Vertical Emittance at 0.9 ms after Injection with Various Beam Intensity

Figure16 shows horizontal and vertical emittance at 0.9 ms after injection with various beam intensity.

The total beam intensity is adjusted by reducing linac peak current with a fixed injection turn number.

Although quantitative comparison with the experimental data is still premature at the moment, the emittance exchange between two transverse planes agrees qualitatively.

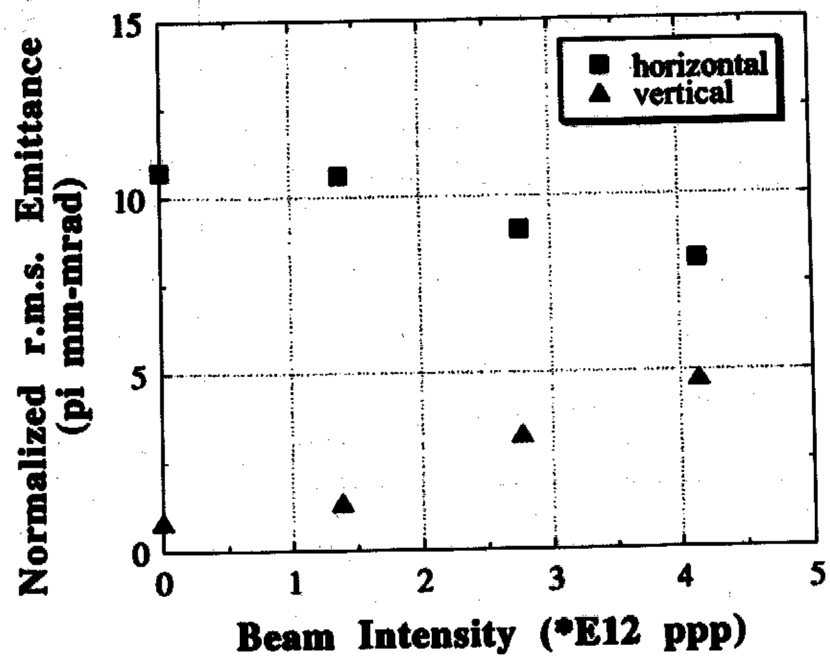


Figure 16: Horizontal and Vertical Emittance at 0.9 ms after Injection with Various Beam Intensity

5.2 The Time Scale of Emittance Exchange

(3D Tracking Simulation with Space Charge)

Figure 17 shows a emittance exchange through accelerating process.

The space-charge dominant phenomenon and the without space-charge phenomenon are compared.

The time scale of emittance exchange shows good agreement with experiment as depicted in Fig. 15.

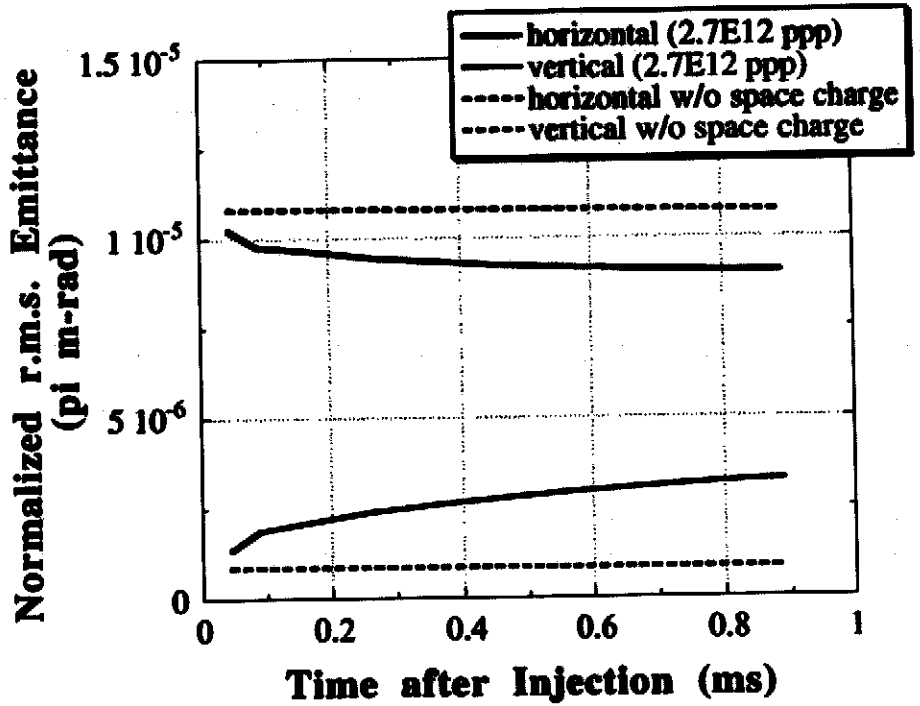


Fig. 17 emittance exchange through accelerating process

5.3 Tune Diagram

The experimental and simulation results imply that the space-charge potential of a beam induces coupling between the horizontal and vertical planes.

Although a linear coupling term in the Hamiltonian, namely x z, is not excited by space charge because of the axial symmetry of a beam, the octupole term ,$x^2 z^2$, exists.

In addition, the present bare tune is (2.17, 2.32), slightly above the coupling resonance line of $2Q_x-2Q_z=0$, and the depressed tune approaches as the beam intensity is increased.

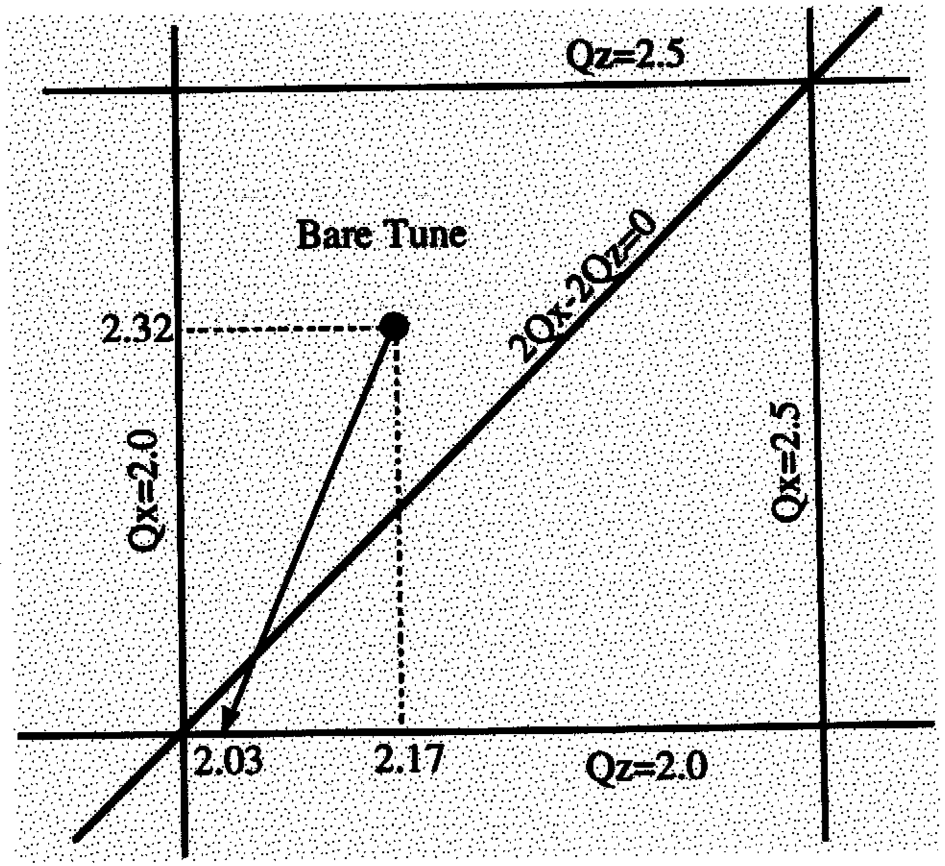


Fig. 18 Tune Diagram

5.4 Emittance Exchange with Three Different Bare tunes

3D tracking simulation with space charge

If the emittance exchange is caused by the coupling resonance, it should be enhanced or suppressed depending on the bare tune.

Figure 6 shows that with three different bare tunes. There are larger exchange at (2.27, 2.32) and no exchange at (2.37, 2.32) where no particles cross the coupling resonance.

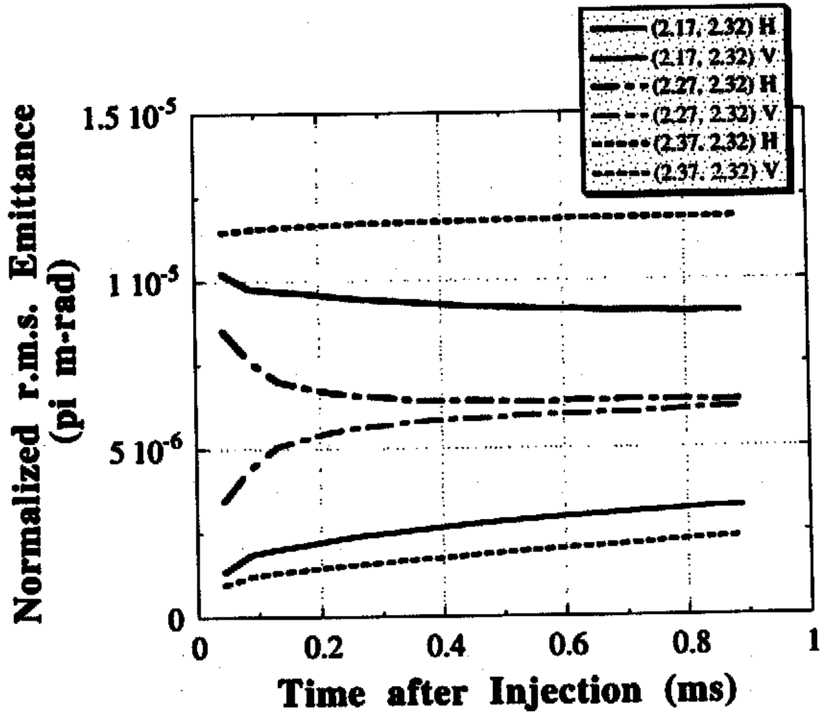


Fig. 19 Emittance Exchange with Three Different Bare tunes

6. SUMMARY

6.1 Injection Scheme and Tune Selection

From both experimental and simulation results, the emittance exchange due to the coupling resonance induced by space charge effects is verified.

The tricky measurement of beam envelopes reveals that the exchange occurs right after injection when the longitudinal bunching proceeds and correspondingly the line density increases.

The similar beam behavior is expected, not only in the KEK booster, but also in a machine where anti-correlated painting scheme inevitably causes unequal transverse emittance.

The same is true in a synchrotron relying on charge-exchange painting injection to increase beam intensity although the careful selection of operating tune wipes out the problem.

6.2 Further Experiment and Simulation

In order to obtain the quantitative agreement between experiment and simulation, further study is still necessary.

One of the difficulties comes from the fact that, in experiment, there is an aperture limit and beam loss occurs.

From the simulation results, it seems that the beam tail in both transverse emittance is developing while the rms emittance flows in one direction.

The definition of the 95% emittance in the experiment is easily affected with beam loss as a result of beam tail.

Another crucial parameter, which is not quite obvious, is the momentum spread of incoming beam. The bunching factor after injection depends on it.